The Petrography and Chemical Composition of the Bruderheim Meteorite[1]

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Abstract. The Bruderheim meteorite, a hypersthene chondrite, has been examined both petrographically and chemically. The minerals of the meteorite are olivine (Fo_{78}), hypersthene (En_{78}), plagioclase (Ab_{86}), apatite, merrillite, chromite, troilite, and metallic iron-nickel. Comparison of petrographic and chemical analyses shows that (1) pyroxene, troilite, and metallic iron-nickel are texturally related; (2) there is substantial CaO contained in the hypersthene; (3) there are important variations in samples the size of a thin section, and it is likely that there are also sampling errors on quantities of the size used for chemical analysis. The texture of the meteorite, including the principal chondrule types, is described.

Introduction. Through the kindness of Professor R. E. Follinsbee, this laboratory, together with a number of others, received a specimen of the Bruderheim meteorite for study. In view of the size of this fall and in view of the fact that so many workers are using it for a variety of studies, it was deemed desirable to make an independent petrographic examination of the meteorite together with an independent chemical analysis. This work was purposely carried out in its entirety without knowledge of the results of other workers.

One polished section and one polished thin section were prepared for microscopic examination. Minerals concentrated from a 1-gram sample with magnetic and heavy liquid techniques were of sufficient purity that refractive index measurements could be easily and accurately made. For chemical analysis, 15 grams of the meteorite were chipped from a 60-gram fragment and crushed in a Plattner mortar to 80 mesh. Those metallic fragments that flattened into plates during the crushing process were separately reduced mechanically to 80 mesh.

A second portion of approximately 25 grams was taken from the 60-gram fragment and reduced to 80 mesh. This portion was separated into 'magnetic' and 'nonmagnetic' fractions with a hand magnet. Separate splits of the powders were used for spectographic and X-ray fluorescence analysis. The results of the latter studies will be reported in a later paper.

Mineralogy. The nonopaque minerals of the meteorite are primarily olivine and pyroxene with minor amounts of feldspar, apatite, and merrillite. The opaque minerals are metallic iron-nickel, troilite and chromite.

Olivine is found as a major constituent of many chondrules and as grains of variable size in the groundmass. The refractive indices (NaD) of the olivine are: $n_x = 1.679 \pm .002$; $n_y = 1.696 \pm .002$; $n_z = 1.715 \pm .002$. The optic angle varies slightly between $2V = +88° \pm 2°$ to $-85° \pm 2°$, suggesting that there is a small variation in composition. The approximate composition of the olivine according to the index data of *Winchell and Winchell* [1951] is $Fo_{78}Fa_{22}$.

Orthopyroxene is abundant in chondrules and the groundmass. It is found as separate grains and as intergrowths with olivine. The pyroxene appears to partly replace olivine crystals in many cases. Some pyroxene grains contain numerous unoriented pyroxene inclusions that are not optically continuous with the host grain but are apparently of the same composition as the host.

The optic properties of the pyroxene are: $n_x = 1.678 \pm .002$; $n_y = 1.687 \pm .002$; $n_z = 1.693 \pm .002$; $2V = -85° \pm 2°$. These properties correspond to hypersthene with a composition $En_{78}Fs_{22}$ [*Hess*, 1960].

Plagioclase occurs as thin, irregular but coarsely crystalline intergrowths between olivine

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grains in a few chondrules and also as interstitial material in the groundmass. Indices of the feldspar are: $n_\gamma = 1.527$; $n_\alpha = 1.538$; they do not vary more than ± 0.002 from these values. In thin section the plagioclase has low relief and low birefringence. It commonly forms a matrix surrounding fine granular pyroxene or olivine in cracks and at grain and chondrule boundaries. The optic angle of the feldspar varies widely from $2V = -50°$ to $2V = +85°$.

The optical properties of the feldspar suggest that it is a highly sodic plagioclase (Ab_{95}) of the high-temperature structural type. In experiments performed by *Smith* [1955] a large variation of optic angle was noted in samples showing incomplete transitions from the high- to the low-temperature structural type. This suggests that the range shown here is indicative of partial inversion from one type to the other.

Apatite ($Ca_5(PO_4)_3 \cdot X$) and merrillite ($3CaO \cdot Na_2O \cdot P_2O_5$) were observed as anhedral crystals, generally free of inclusions, interstitial to the chondrules and the silicate groundmass. A small portion of these minerals is found in the chondrules. Apatite has $n_0 = 1.656$, $n_e = 1.652$ and merrillite has $n_0 = 1.624$, $n_e = 1.620$. They are of approximately equal abundance.

Troilite and metallic iron-nickel are present in small amounts in the chondrules, but the majority is present as irregular masses which are interstitial to the silicate portions of the groundmass. At the time of examination of the thin section and polished section, films of iron oxides were observed but it is likely that these were entirely due to atmospheric oxidation of the metallic phase.

Chromite is present in only small amounts. It is found predominantly in the silicate portions of the meteorite, including the chondrules and forms small, irregular grains which rarely reach a diameter of 1 mm.

Texture. The most conspicuous textural elements are the chondrules, which range from ½ to 3 mm in diameter and have varying internal structures. Thirty-five chondrules are well developed in the thin section and perhaps as many again are present as poorly developed, indistinct, or fragmental chondrules. The well-developed chondrules were examined individually and grouped according to mineralogy. It was found that the mineralogical groupings of the chondrules correspond closely to their textural groupings; only three chondrules were seen that might be considered to be made up of two types, and the separate parts of these chondrules conformed to the mineralogical groupings.

The three principal types of chondrules are mineralogically composed of (1) pyroxene, (2) pyroxene and olivine, and (3) olivine. The pyroxene chondrules are composed of 95 to 100 per cent hypersthene with only insignificant amounts of olivine. Scattered troilite and iron-nickel inclusions, about 0.02 mm in diameter, can be seen within the chondrules and somewhat larger and more abundant opaque grains exist near the borders. The chondrules are constructed of indistinct to well-defined sets of parallel pyroxene laths averaging 0.02 mm in width and of variable length. Complex intergrowths of lath sets produce a radiating appearance in some chondrules, although no pyroxene chondrule shows a well-developed point from which all laths radiate. With one exception these chondrules are not sharply defined and appear to grade into the groundmass. The exception is a well-developed pyroxene chondrule of distinct outline and made up of coarser laths.

The chondrules of the olivine-pyroxene type are composed of approximately equal amounts of olivine and hypersthene. These chondrules are characterized by a framework of olivine laths about 0.01 mm thick and up to 1 mm in length, a discontinuous rim of olivine crystals about 0.1 mm in diameter, and interstitial fine-grained pyroxene in the interior portions reaching 0.05 mm in grain size. The olivine in the core and rim is in optical continuity whereas the pyroxene is variable in optic orientation. There are a few opaque inclusions scattered throughout these chondrules.

The chondrules that are composed predominantly of olivine can be further classified on the basis of other phases that are present. Those chondrules that contain small amounts of pyroxene and plagioclase are similar in structure to the olivine-pyroxene chondrules, but are different in that they have much coarser olivine laths and rims. A typical example has a parallel set of olivine laths approximately 0.1 mm in width that is in parallel orientation with a rim that is approximately 1 mm in width. Interstitial to the laths are anhedral pyroxene grains no more than 0.03 mm in size. The pyroxene

TABLE 1. Frequency of Chondrules in the Bruderheim Meteorite by Mineralogical Type

Chondrule Type	Number
Pyroxene	13
Pyroxene-olivine	4
Olivine	14
6 olivine and pyroxene	
5 olivine and plagioclase	
3 olivine and fine-grained aggregate	
Composite	3
Other	1
Total	35

forms about 15 per cent of the chondrule, and a small amount of plagioclase is also present. In general, these olivine chondrules that contain significant amounts of feldspar have very thick olivine laths.

A second type of olivine chondrule consists of an aggregate of randomly oriented olivine crystals together with 5 to 40 per cent of fine-grained interstitial material composed chiefly of olivine. The fine-grained material is very similar in appearance to the finest-grained portions of the groundmass. Opaque inclusions are abundant in these chondrules. The boundaries of the chondrules of this type are generally indistinct, and there are a few aggregates of olivine and fine interstitial material present in the groundmass that may actually be chondrules, but cannot be positively identified as such.

Only three chondrules were observed that could not be placed uniquely into one of the major groups. These chondrules are made up of segments that exhibit the pyroxene-olivine structure and the coarse olivine structure. The structures within these composite chondrules reflect mineralogy in the manner of the major groups.

In addition, there is one chondrule that is in a group by itself and is worth describing separately. It is quite round in cross section and approximately 3 mm in diameter. The center is composed of an irregular intergrowth of pyroxene and olivine of about 0.5 mm average grain size. The outer one-half of the chondrule consists of an aggregate of olivine of finer-grain size than the center and which contains only small amounts of pyroxene and apatite. Close to the rather sharp boundary of coarse- and fine-grained portions is a zone rich in iron-nickel grains with some troilite. The outer boundary surrounds a rim composed of pyroxene and troilite, containing only small amounts of metallic iron-nickel.

The thirty-five chondrules which were studied in the thin-section are tabulated by chondrule mineralogy in Table 1. The predominance of chondrules that fall into such a small number of groups suggests that there are at least three distinct mineralogical types of chondrules and that the textural and mineralogical variations are not due to random cutting of a single chondrule type by the thin section.

The groundmass of the meteorite is composed of a very inequigranular aggregate of olivine, pyroxene, feldspar, phosphates, and the opaque phases. The texture is in part fragmental, but there are many places where pyroxene can be seen to embay olivine grains. There is also a suggestion that the troilite and metallic iron-nickel are associated with pyroxene. Most of the large pyroxene grains in the groundmass are found near concentrations of opaque material. The feldspar is found in irregular patches where it is always observed to enclose numerous fine grains of pyroxene or olivine. The apatite and merrillite as well as most of the troilite and metal occur as irregular grains and granular aggregates that are interstitial to the silicate portions of the groundmass.

Modal analysis. A modal analysis was made

TABLE 2. Modal Analysis of the Bruderheim Meteorite

Mineral	Volume, %	Assumed Specific Gravity	Weight, %
Pyroxene	45.83	3.35	42.26
Olivine	42.83	3.45	40.67
Feldspar	0.50	2.6	0.36
Apatite and merrillite	0.43	3.0	0.35
Metallic	3.54	7.8	7.60
Troilite	5.08	4.8	6.71
Chromite	0.54	5.7	0.85
Holes	1.25	3.5*	1.21

* Holes weighted as average density of meteorite.

TABLE 3. Chemical Composition of the Bruderheim Meteorite

	1	2	3	Average	Magnetic	Non-magnetic	Composite
SiO_2	39.56	39.54		39.55	15.51	43.31	39.84
TiO_2	0.12	0.12		0.12	0.05	0.12	0.12
Al_2O_3	2.15	2.15		2.15	0.98	2.36	2.19
Met. Fe	7.44*	7.18†		7.31	53.40‡	0.36‡	6.97
FeO + Fe_2O_3(as FeO)	13.80	13.55		13.89	6.90	14.97	13.87
MnO	0.32	0.32		0.32	n.d.	0.35	0.31
CaO	1.76	1.79		1.78	0.78	1.94	1.80
MgO	24.66	24.71		24.69	7.77	27.16	24.71
Na_2O	0.99	0.99		0.99	n.d.	1.07	0.94
K_2O	0.12	0.11		0.12	n.d.	0.12	0.10
H_2O^+	0.14	0.17		0.16	n.d.	0.18	0.16
H_2O^-	0.05	0.03		0.04	0.04	0.01	0.01
P_2O_5	0.28	0.27		0.28	n.d.	0.30	0.26
FeS	6.56	6.59		6.58	2.21	7.25	6.63
Ni(as metal)	1.22	(1.39)§	1.22	1.22	9.36	0.12	1.28
Cr_2O_3	0.53	n.d.||		0.53	0.27	0.58	0.54
TOTAL	99.70	99.44||		99.73	97.27	100.16	99.73
Total Fe	22.35	21.90§	22.23	22.29	60.16	16.62	22.04

* Riott's procedure.
† $HgCl_2$ procedure.
‡ Average of one determination each by Riott's and $HgCl_2$ procedures.
§ Discarded in averaging.
|| Cr_2O_3 from no. 1 is used.

by counting 2500 points on a 10-cm^2 area of the polished thin section in both reflected and transmitted light. The proportions of the nonopaque minerals were measured in transmitted light. The proportions of opaque minerals and the ratio of opaque to nonopaque minerals were measured in reflected light. The two measurements were combined to obtain the modal data which are shown in Table 2.

Chemical analysis. A number of the chemical procedures were adapted from those used by Lee C. Peck and J. J. Fahey at the U. S. Geological Survey.

Portions of the crushed sample that were used for the various determinations were separated with a sample-splitter, with the exception that grab-samples were used in the analysis of the 'magnetic' fraction.

A 1-gram portion was used for the determination of H_2O^-, SiO_2, TiO_2, Al_2O_3, CaO, MgO, and total iron. H_2O^- was determined from the loss in weight at 105°C. After fusion with sodium carbonate, silica was recovered by a double dehydration with hydrochloric acid. The R_2O_3 group was precipitated with ammonia, the precipitate was dissolved and aliquots were taken for the various determinations. Silica present in the ammonia precipitate was recovered and the weight was added to that previously determined. TiO_2 was determined colorimetrically with hydrogen peroxide. Total iron was determined by reduction with silver and titration with potassium dichromate. Al_2O_3 was determined gravimetrically by precipitation with 8-hydroxyquinoline [see *Flagg*, 1948]. Calcium was precipitated twice as the oxalate, ignited and weighed as the oxide. Magnesium was precipitated twice with phosphate, ignited, and weighed as pyrophosphate. The manganese present in the pyrophosphate was determined, and the weight was corrected for its presence.

Total water was determined by the Penfield method [see *Hildebrand, Lundell, Bright, and Hoffman*, 1953, pp. 827–828], with lead oxide as a retainer. The value for H_2O^+ was obtained by subtracting H_2O^- from total water.

Alkalies were determined in a 0.5-gram sample, essentially in the manner outlined by *Brannock and Berthold* [1953].

Manganese and phosphorous were determined

TABLE 4. Comparison of Chemical Analysis of the Bruderheim Meteorite with the Composition Calculated from the Modal Analysis

Constituent	Modal Analysis	Average Chemical Analysis
SiO_2	40.39	39.55
Al_2O_3	0.07	2.15
FeO	12.22	13.89
MgO	31.40	24.69
CaO	0.18	1.78
Na_2O	0.04	0.99
P_2O_5	0.17	0.28
Fe–Ni	7.60	8.53
FeS	6.71	6.58
Holes	1.21	

in aliquots of a solution of 0.5 gram of meteorite. The procedure used for P_2O_5 was that of *Kitson and Mellon* [1944]. MnO was determined with the procedure of *Williard and Greathouse* [1917].

Total nickel, chromium, and sulphur were determined in a 1-gram portion after fusion with a sodium carbonate-potassium nitrate flux. Chromium was determined colorimetrically as the dichromate, sulphur gravimetrically by precipitation with barium chloride, and nickel gravimetrically by precipitation with dimethylglyoxime.

Metallic iron was determined by *Riott's* [1941] procedure and by the mercuric-chloride procedure described by *Lundell, Hoffman, and Bright* [1931]. Generally, Riott's procedure yields the higher result for metallic iron. Experiments with other meteorites have not yet indicated the cause of the difference.

The concentration of iron as oxides, reported as FeO, was obtained by subtracting the sum of metallic iron and iron as sulphide from total iron.

The analytical results are shown in Table 3. It can be seen that the analysis is in satisfactory agreement with the composite result derived from independent analyses of the 'magnetic' and 'nonmagnetic' splits.

Comparison of modal and chemical analyses. By assuming the composition of each of the mineral phases to be that deduced by optical means, an approximate chemical composition can be deduced from the modal data. The results of such a calculation are compared with the chemical analysis in Table 4.

The calculated chemical analysis is similar to the chemical analysis but is divergent for a number of possible reasons:

1. The surface of the polished section is marked by a number of holes representing plucking out of grains during polishing. To the extent that some mineral may be preferentially plucked out, the modal analysis is in error.

2. The proportions of the minerals may not have been accurately determined microscopically. This in great part is due to the small size sample area, which is not precisely representative of the entire meteorite. It is also difficult to count accurately the tenuous feldspar grains and oxide films.

3. The presence of CaO and Al_2O_3 in the pyroxene and TiO_2 and Cr_2O_3 in either the pyroxene or chromite cannot be determined by optical methods. This will lead to an underestimation of the abundances of these oxides.

It should be noted that the proportions of troilite and metallic iron-nickel found in the modal analysis agree with those found chemically.

To attempt a further correlation between chemical and modal data a modified normative calculation was made on the silicate portion 'average,' 'magnetic,' and 'non-magnetic' chemical analyses. This calculation is different from the usual CIPW norm in that the FeO/MgO ratios of the pyroxene and olivine were chosen to be the values deduced from the optical properties of the minerals. The effect of this assumption is to free a certain amount of FeO for the oxide phases present in the meteorite and, in doing so, to make up for the lack of a figure for Fe_2O_3 in the chemical analysis. It is also assumed that all the Na_2O is combined as albite and that the excess CaO and Al_2O_3 are present in the pyroxene phase. This assumption is slightly in error because of the small amount of calcium in the plagioclase and sodium in the merrillite. The results are tabulated in Table 5.

A number of conclusions can be drawn from these calculations:

1. There is a concentration of pyroxene with the metallic phase in the magnetic fraction. This

TABLE 5. Modified Normative Calculation of Chemical Analyses

		Average	Magnetic	Nonmagnetic	
($KAlSi_3O_8$)	or	0.8	...	0.7	
($NaAlSi_3O_8$)	Ab	9.9	1.6	9.6	
(Mg, Fe, Ca, Al)(Al, Si)O_3	py	41.9	86.4	42.8	
(Mg, Fe)SiO_4	ol	41.2	...	40.7	Silicate phase recalculated to 100%
$FeO \cdot Cr_2O_3$	Cr	0.9	1.3	0.9	
$FeO \cdot TiO_2$	Il	0.3	0.3	0.2	
$3\ CaO \cdot P_2O_5$	Ap	0.7	...	0.7	
	FeO	4.2	10.5	3.9	
		100.0	100.1	99.9	
	$MgSiO_3$	69.1	69.2	70.2	Pyroxene Composition recalculated to 100%
	$FeSiO_3$	21.2	21.8	21.7	
	$AlAlO_3$	1.2	3.2	1.1	
	$CaSiO_3$	8.5	5.9	7.0	
		100.0	100.1	100.0	

would be predicted from the distribution of pyroxene in thin section where it is observed that there tend to be concentrations of pyroxene around opaque grains in the groundmass. During the crushing process there would be a selective concentration of pyroxene in the metal phase due to embedding of the silicate grains.

2. There is a significantly greater amount of uncombined FeO in the magnetic portion which would correspond to concentration of oxidized metallic iron-nickel. Chromite is concentrated relative to silicates in the magnetic fraction.

3. The pyroxene probably does contain approximately 3 per cent CaO. This is unusual because orthopyroxenes do not have a high tolerance for CaO and because the feldspar would seem the more likely location of the CaO. The general similarity of the calculated CaO and Al_2O_3 for the pyroxenes of the three analyses strongly suggest that most of the CaO and some Al_2O_3 are in the pyroxene. The high Al_2O_3 content of the pyroxene calculated for the magnetic fraction is due to the lack of analyses for alkalis in this fraction. A value for Na_2O was chosen to eliminate a small amount of free SiO_2 in the modified norm. If there is approximately 0.4 per cent Na_2O in the magnetic fraction, the alumina content of the pyroxene would be the same as calculated for the other two analyses. Assigning more alkali, alumina, and SiO_2 to feldspar increases the proportion of olivine:pyroxene and thus increases the calculated CaO of the pyroxene. The high value of calcium in the pyroxene suggests the possible presence of a diopsidic clinopyroxene. None was observed in the thin section.

4. By comparison of the norm with the modal analysis a fairly large sampling error is demonstrated on a sample of the size of the thin section. This is particularly true of the plagioclase which has a very irregular distribution, but it also appears to be the case with the free iron oxides. The effect of the underestimation of these components is considerable in the modal analysis.

5. When a weighted average is taken of the 'magnetic' and 'nonmagnetic' analyses, there appears to be a lower olivine:pyroxene ratio in the norm of the 'composite' analysis as compared to the 'average' analysis. It is therefore suggested that sampling errors can be noticeable on aliquots of the size taken for chemical analysis.

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